Well Known...to a Few People

Attribution of Excess Atmospheric CO_2 and Resulting Global Temperature Change to Fossil Fuel and Land-Use Change Emissions

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Don't pass this poster by!

Your children's and your grandchildren's future depends on this.

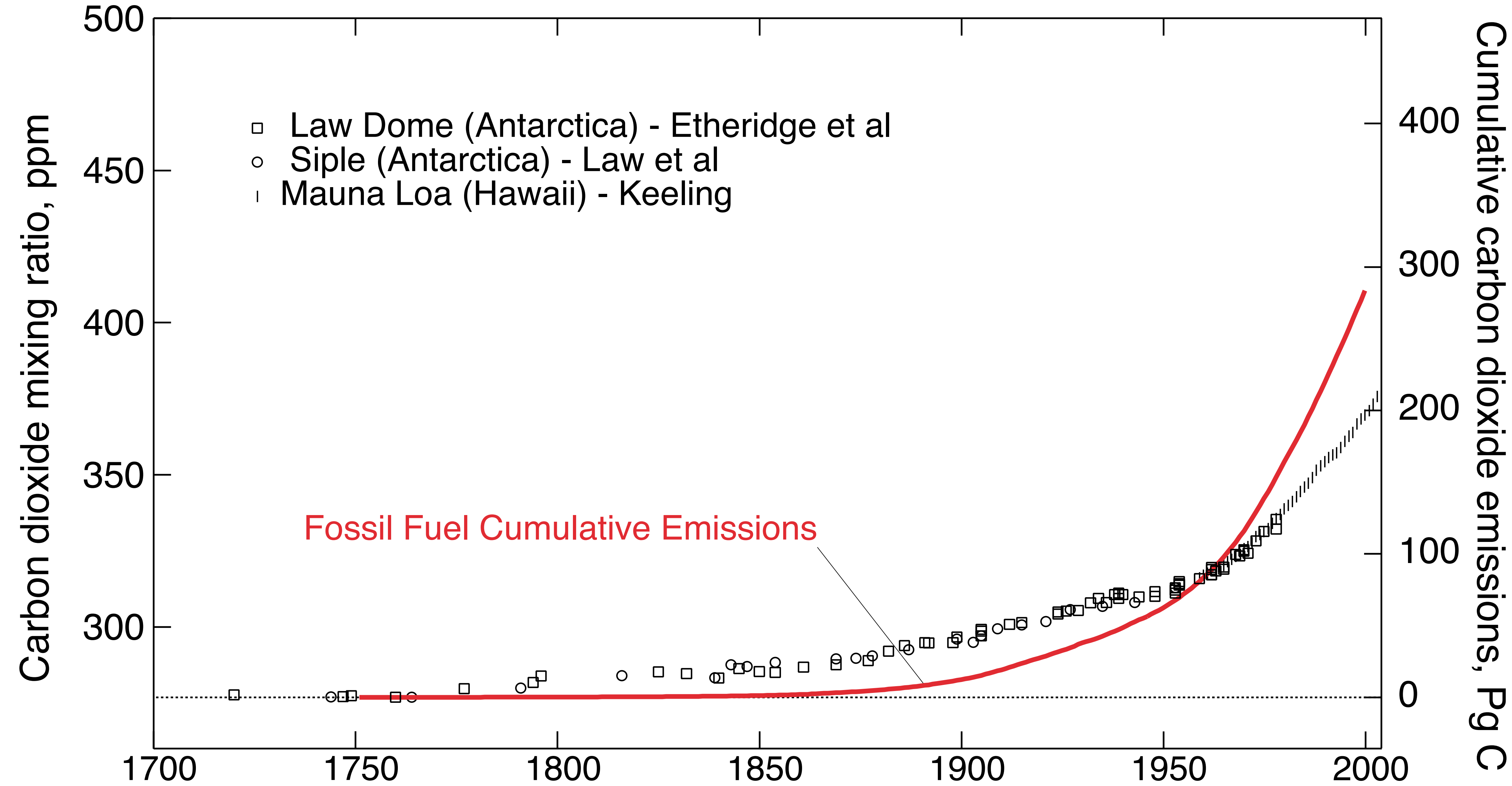
The Key Questions:

Is atmospheric CO_2 well enough understood to permit confident policymaking?

Do we understand CO_2 ***sources***? Do we understand CO_2 ***sinks***?

BOTTOM LINE: The adjustment time of excess atmospheric CO_2 inferred from observations is 45 ± 10 years.

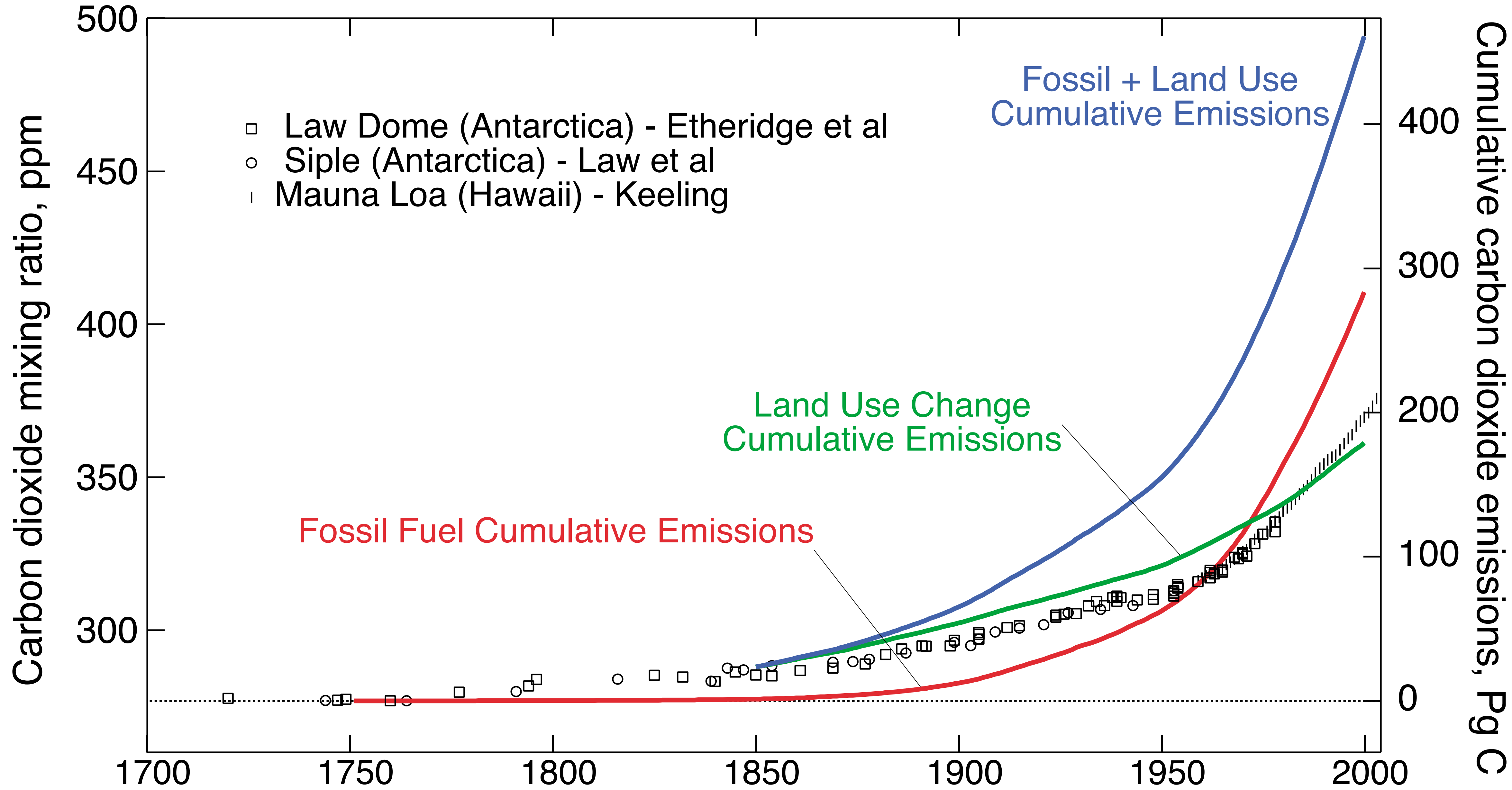
Historically atmospheric CO_2 has substantially exceeded cumulative fossil fuel emissions



How can this be?

Lift up to see why!

Atmospheric CO_2 and Cumulative Fossil Fuel and Land-Use Change Emissions



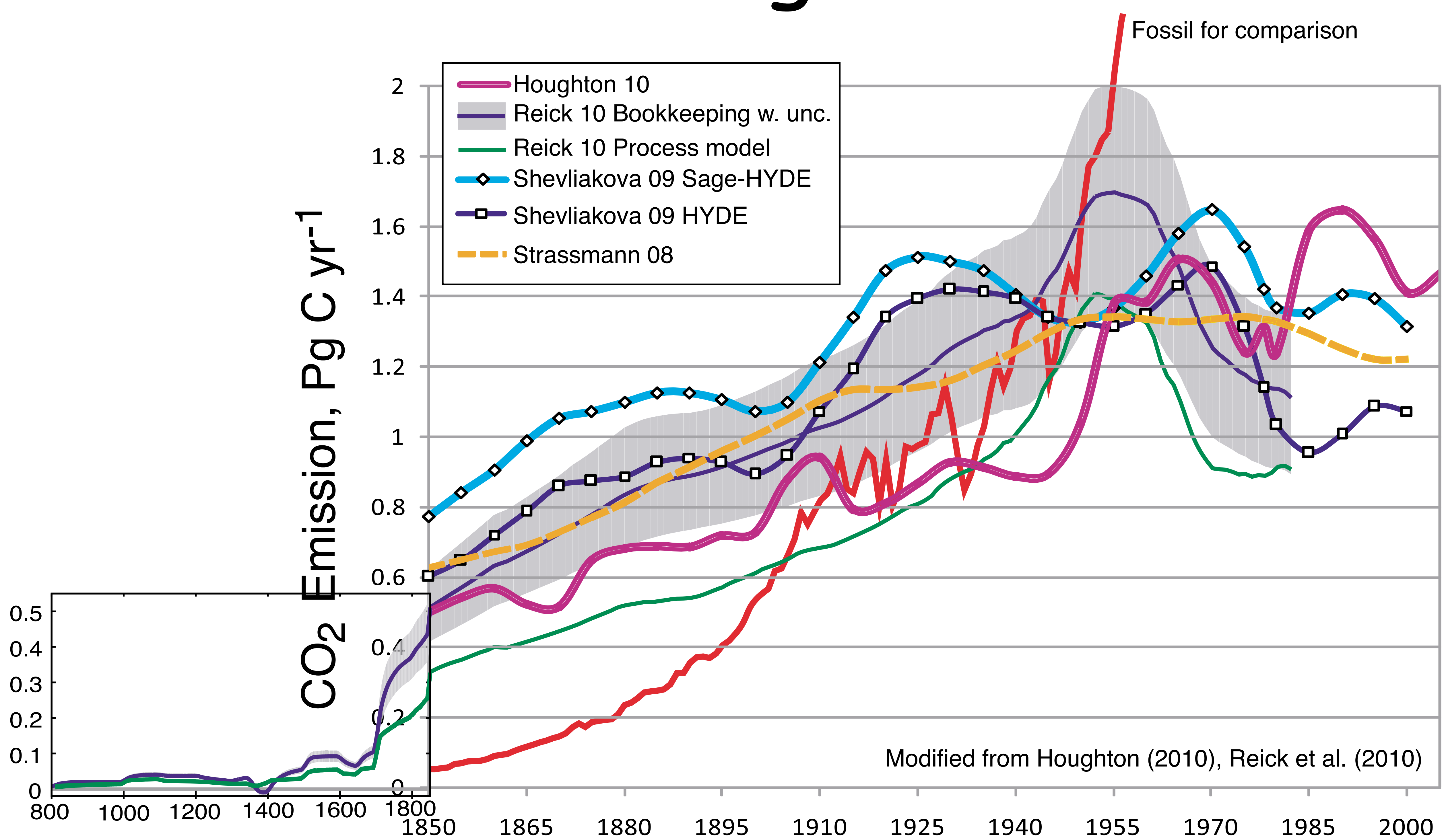
CO_2 emissions from land-use change (mainly net of deforestation and afforestation) resolve the paradox.

Land-use change emissions dominated until about 1965 and are still about 1/3 of total cumulative emissions.

This was well understood by Keeling (AGU Monograph, 1989), Broecker and Peng (*Tracers in the Sea*, 1982), Stuiver (*Science*, 1978).

Land-use emissions must be accounted for in CO_2 budget studies.

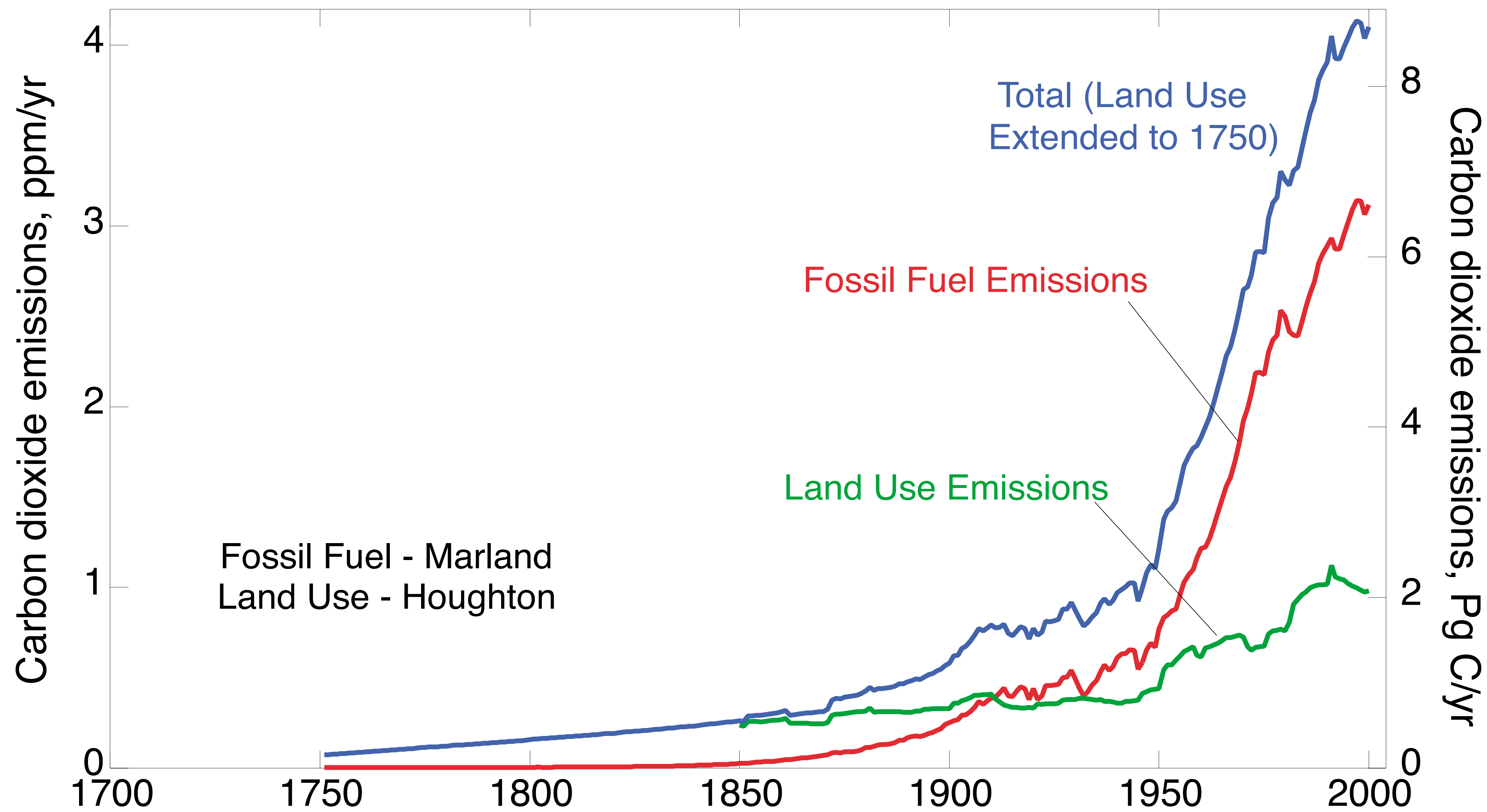
Land-Use Change Emissions



Systematic investigation by Houghton from historical land-clearing records.

Similar results by other investigators.

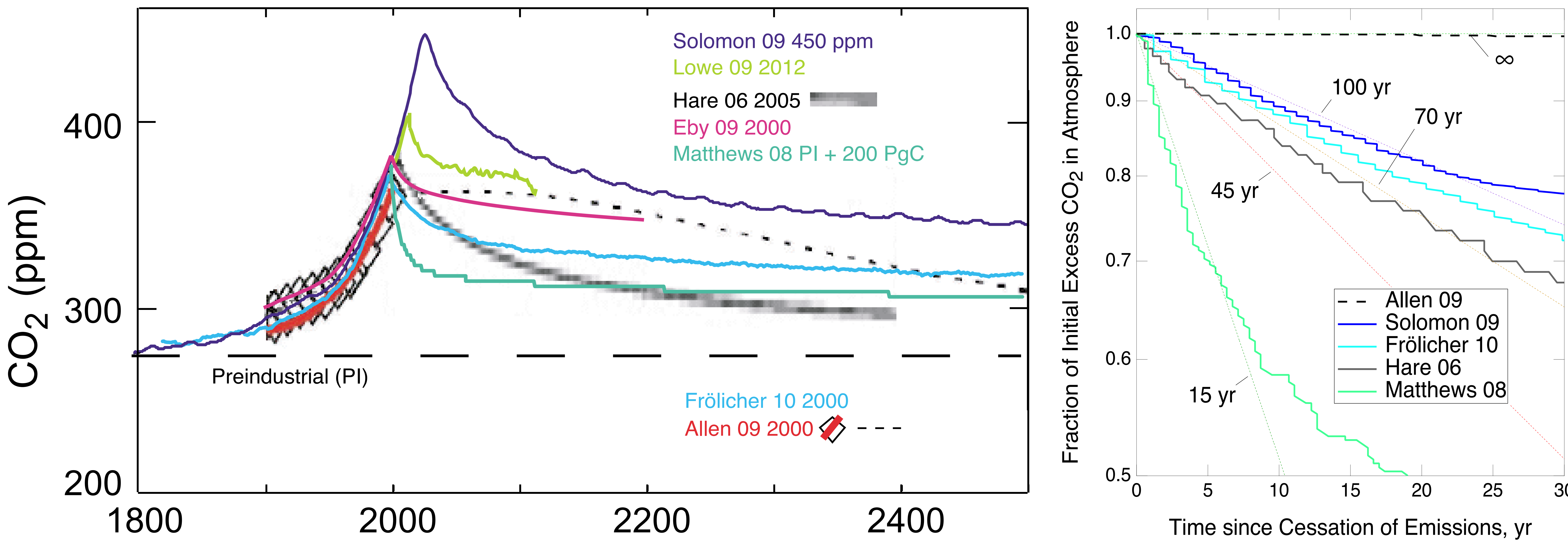
Fossil Fuel and Land-Use Change CO_2 Emissions



Fossil fuel emissions started much later than land-use change emissions and did not equal land-use change emissions until the early twentieth century.

Land use emissions are still about 1/5 of total CO_2 emissions.

Removal of CO_2 from the Atmosphere



Current models differ greatly in expected decrease in atmospheric CO_2 following hypothetical abrupt cessation of emissions.

Current models suggest much excess CO_2 remains even after multiple centuries.

Adjustment time characterizing initial removal of CO_2 varies greatly among models.

This situation is unsatisfactory for policy purposes.

Can observationally based understanding improve the situation?

First-Order Decay Model

Hypothesis: Excess CO_2 (above preindustrial) decays to preindustrial at a rate that is proportional to the excess.

Premise: Preindustrial CO_2 mixing ratio (280 ppm) is natural ***compensation point*** of unperturbed biosphere.

Implication: If anthropogenic emissions were abruptly halted, CO_2 mixing ratio would exhibit exponential decay to the preindustrial 280 ppm.

Approach: Treat atmosphere and ocean-mixed layer as a coupled reservoir. About 10% of the excess CO_2 is in the ocean mixed layer.

CO_2 loss rate is difference between emissions and increase in CO_2 in the atmosphere plus ocean mixed layer, inferred from increase in atmospheric mixing ratio.

$$\frac{d[\mathrm{CO_2}]}{dt} = Q - k([\mathrm{CO_2}] - [\mathrm{CO_2}]_{\mathrm{pi}})$$

Q is emission rate, Pg C yr^{-1}.

$[\mathrm{CO_2}]$ is amount of CO_2 in atmosphere plus ocean mixed layer, Pg C; subscript "pi" denotes preindustrial.

k is ***effective first order rate constant***, yr^{-1}.

$$Q - \frac{d[\mathrm{CO_2}]}{dt} = k([\mathrm{CO_2}] - [\mathrm{CO_2}]_{\mathrm{pi}})$$

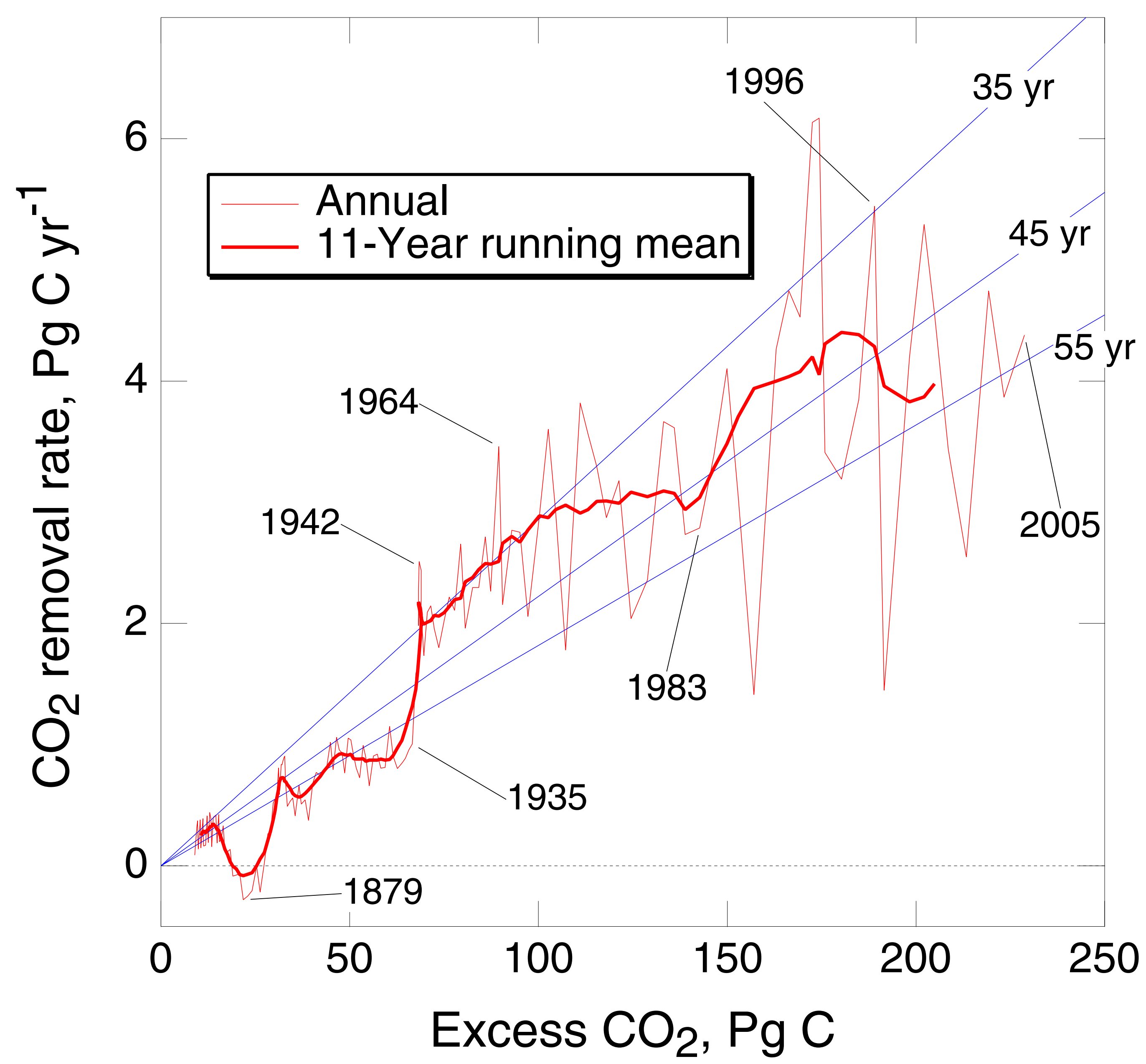
$$\tau \equiv k^{-1} = \frac{[\mathrm{CO_2}] - [\mathrm{CO_2}]_{\mathrm{pi}}}{Q - d[\mathrm{CO_2}]/dt}$$

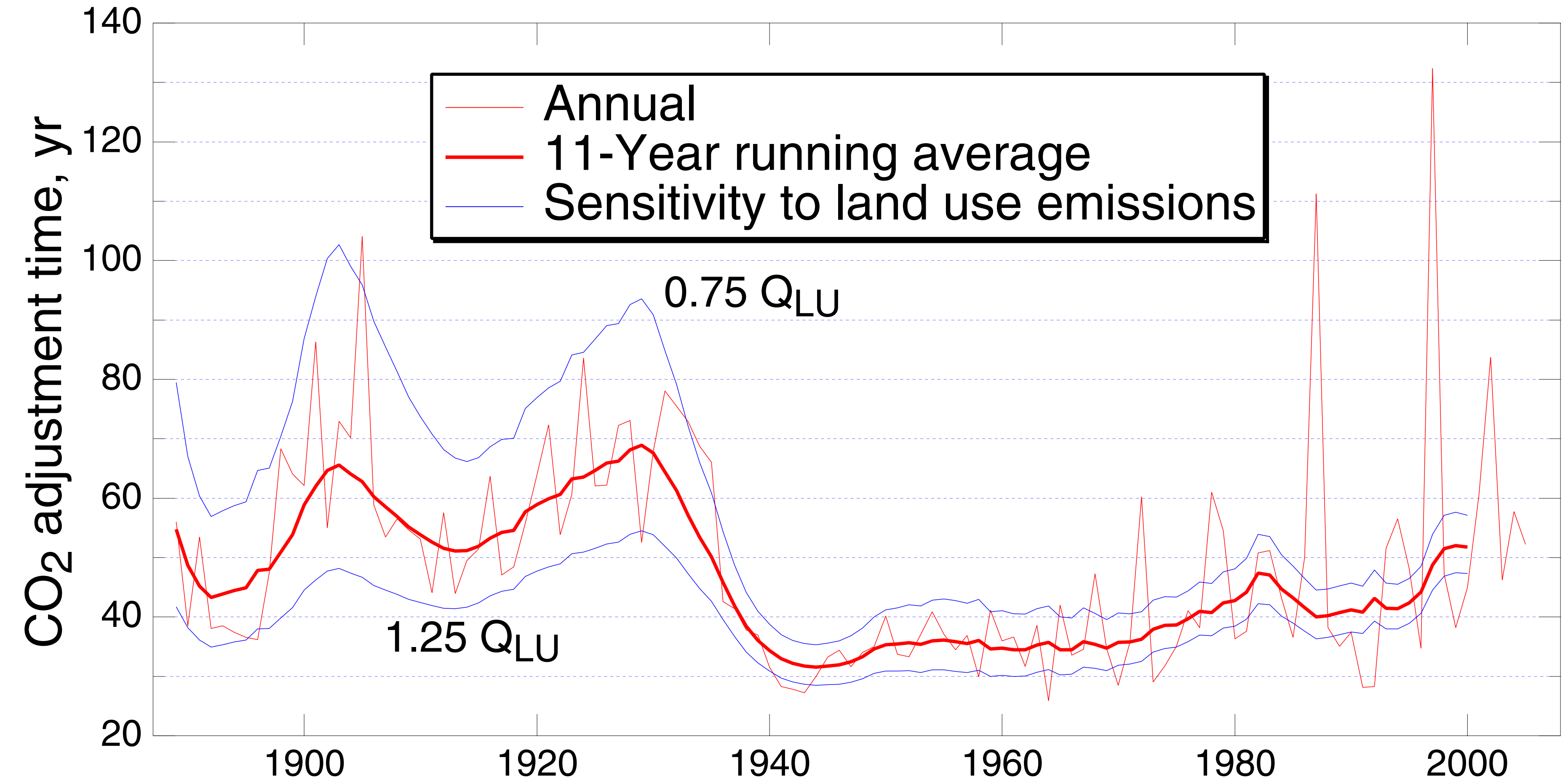
τ is ***adjustment time*** of excess CO_2.

Implies plot of $Q - d[\mathrm{CO_2}]/dt$ vs $[\mathrm{CO_2}] - [\mathrm{CO_2}]_{\mathrm{pi}}$ is linear with zero intercept. Slope is removal rate constant.

Suggests $\left([\mathrm{CO_2}] - [\mathrm{CO_2}]_{\mathrm{pi}}\right) / (Q - d[\mathrm{CO_2}]/dt)$ would be constant or reflect adjustment time that varies temporally or with the amount of CO_2 in the atmosphere.

Test the Model and Determine the Adjustment Time



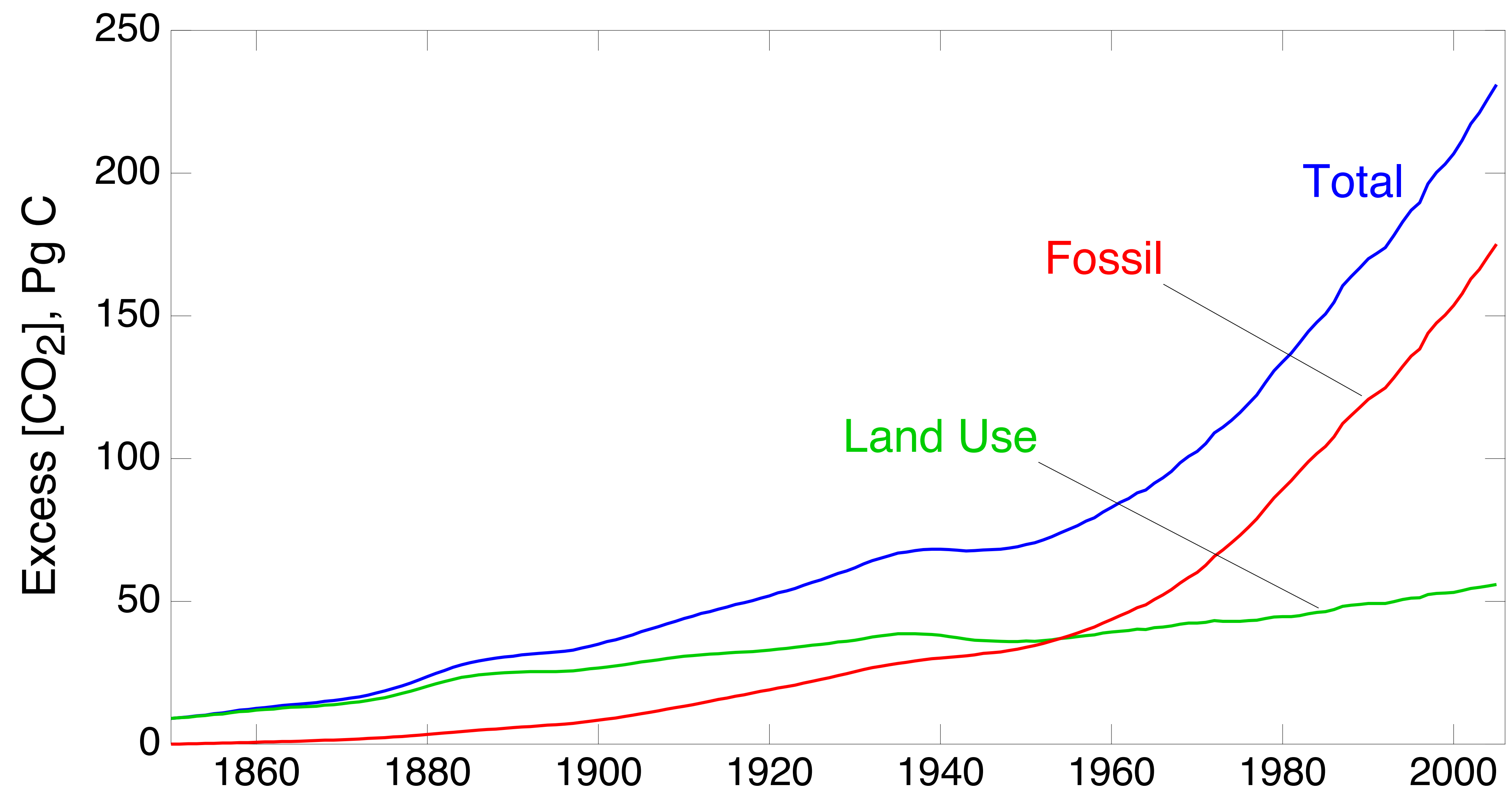


Adjustment time τ is 45 ± 10 yr. See also Hansen and Sato, *PNAS*, 04; Gloor, *ACP*, 10.

No evidence of substantial decrease in CO_2 removal rate constant k with age or amount of CO_2 in reservoir.

Somewhat sensitive to uncertainty in land-use emissions.

Attribution of Excess CO_2 to Land-Use Change and Fossil Fuel Emissions



Model allows confident attribution of excess CO_2 to land-use change vs fossil emissions.

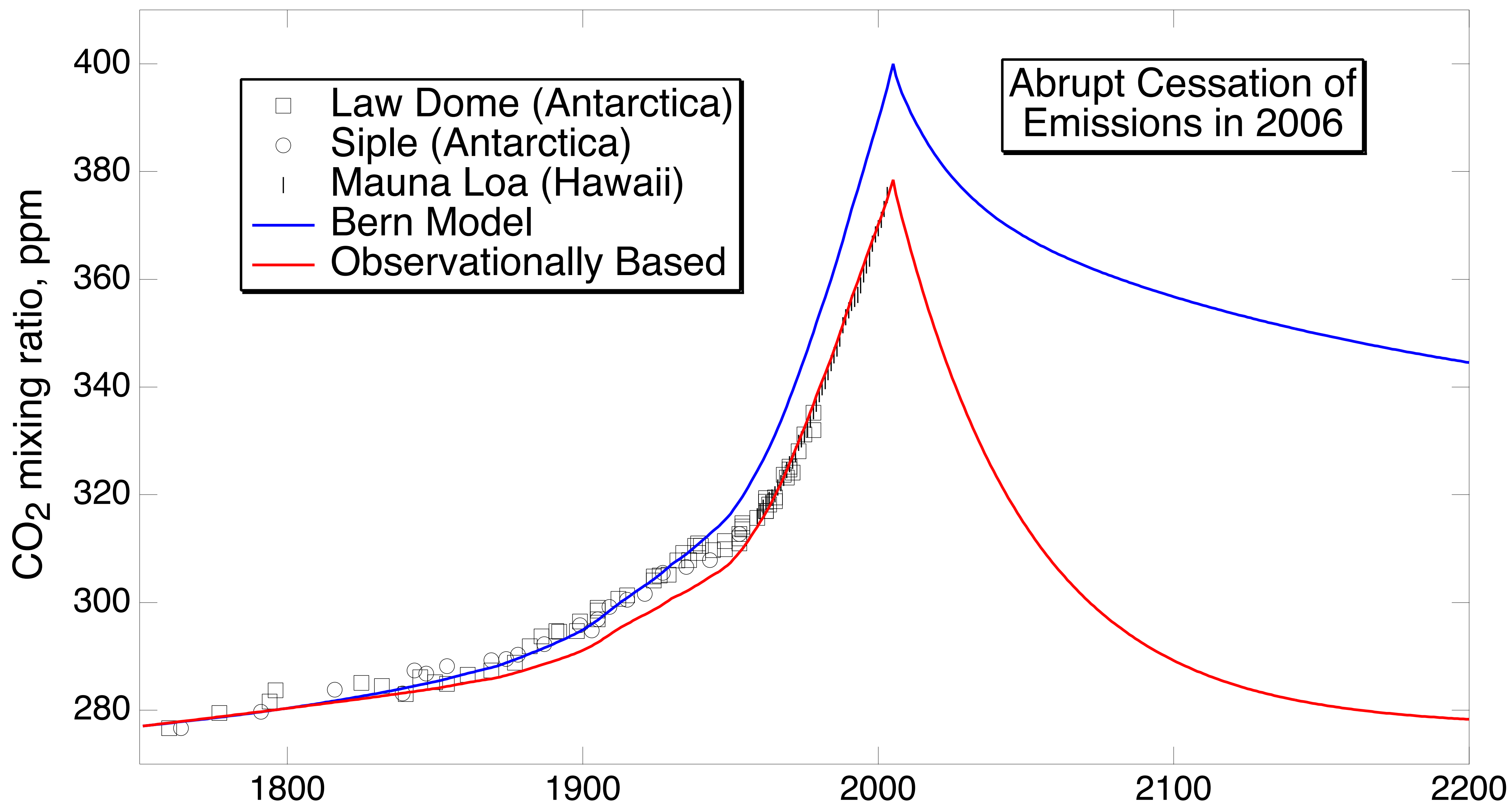
Land-use change emissions dominated excess CO_2 mixing ratio and forcing until about 1950.

Land-use change emissions account for about 1/4 of present total excess CO_2 mixing ratio and forcing.

Contrast with Bern Model

Bern Model (Joos, *GBC*, 2001) assumes decrease in atmospheric CO_2 is dominated by uptake into oceans. See Box 1: Uptake of CO_2 into the Oceans.

Decrease in removal rate constant with time subsequent to emission is due to saturation of ocean. See Box 2: Impulse Response Function for CO_2.



Models comparably reproduce observed CO_2 mixing ratios.

Observationally based model yields much more rapid and complete recovery of preindustrial CO_2 mixing ratio following abrupt cessation of emissions.

Discussion

How can two such different models reproduce the observed CO_2 mixing ratio so well?

Both impulse response profiles exhibit similar rapid decrease in initial 40 years. Because of exponential increase in CO_2 emissions (1/e time ~40 years) most of the incremental CO_2 in the atmosphere at any observation time is young.

Conclusions

Land-use change emissions dominated excess CO_2 mixing ratio and forcing until about 1950 and account for about 1/3 of cumulative CO_2 emissions, 1/4 of present excess CO_2, and 1/5 of present CO_2 emissions.

Linear decay model is well supported by observations. No evidence of substantial decrease in CO_2 removal rate constant with age or amount of CO_2 in reservoir. Adjustment time τ is 45 $\pm$ 10 yr.

No evidence that if CO_2 emissions were halted, CO_2 would plateau out to a value substantially greater than preindustrial.

Policymakers can act with confidence that reduction in CO_2 emissions will be rewarded by reduction in mixing ratio of atmospheric CO_2.

Box 1. Uptake of CO_2 into the Oceans

Assume equilibrium between atmosphere and ocean mixed layer (100 m). Then the mass of excess CO_2 in the atmosphere + ocean mixed layer is 10% greater than that in the atmosphere given by atmospheric mixing ratio above preindustrial. The time constant for achieving this equilibrium is about 1 year.

For equilibrium with the deep ocean (3800 m) the atmospheric fraction of excess CO_2 is about 20%. This is the basis of the commonly assumed non-zero excess atmospheric CO_2 at large time following cessation of emissions. No uptake by the biosphere.

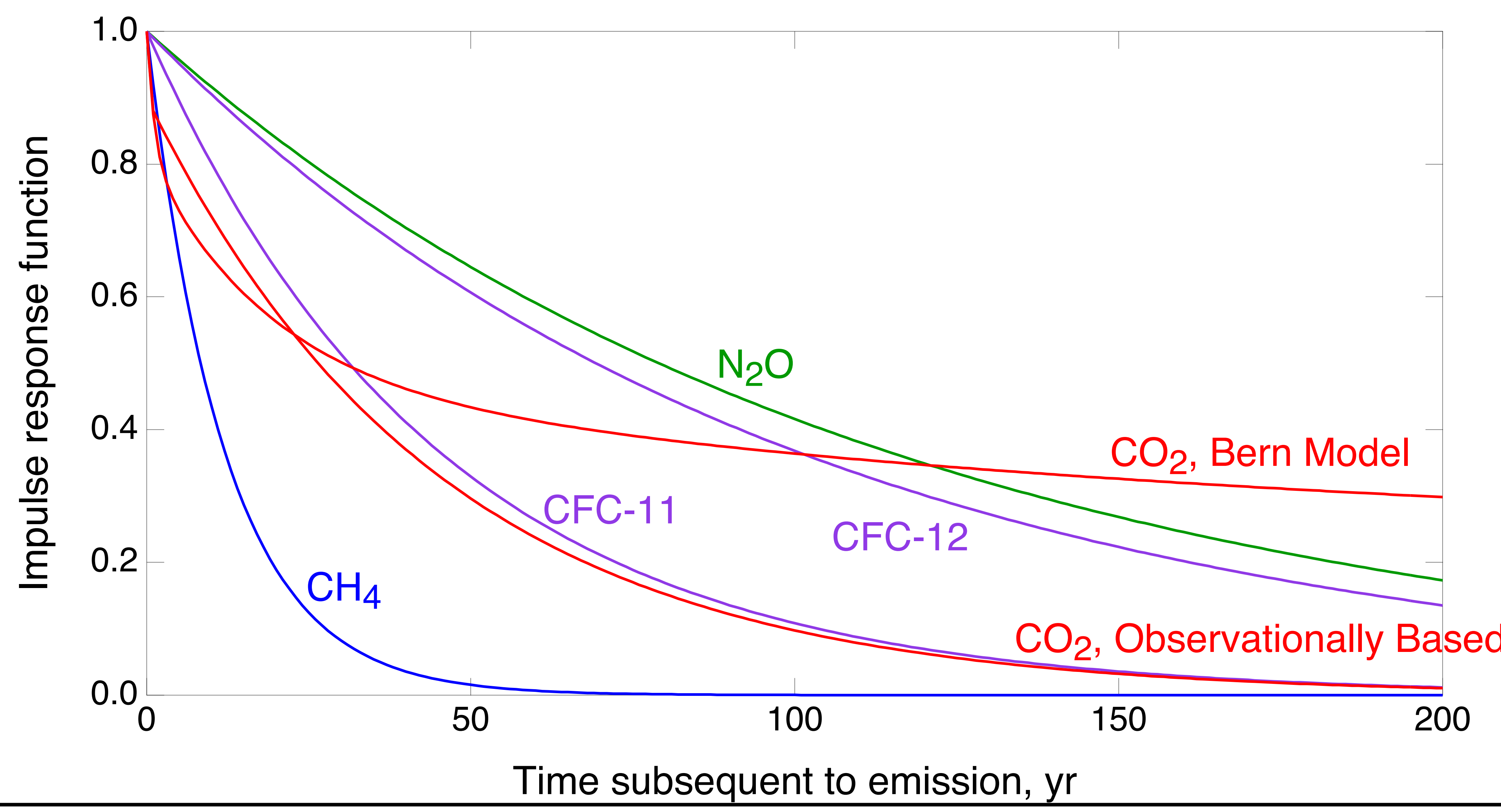
Box 2. Impulse Response Functions for CO_2 and Other Long-Lived GHGs

Impulse Response Function: The fraction of a given pulse of material introduced into the atmosphere at time t remaining at time t + Δt

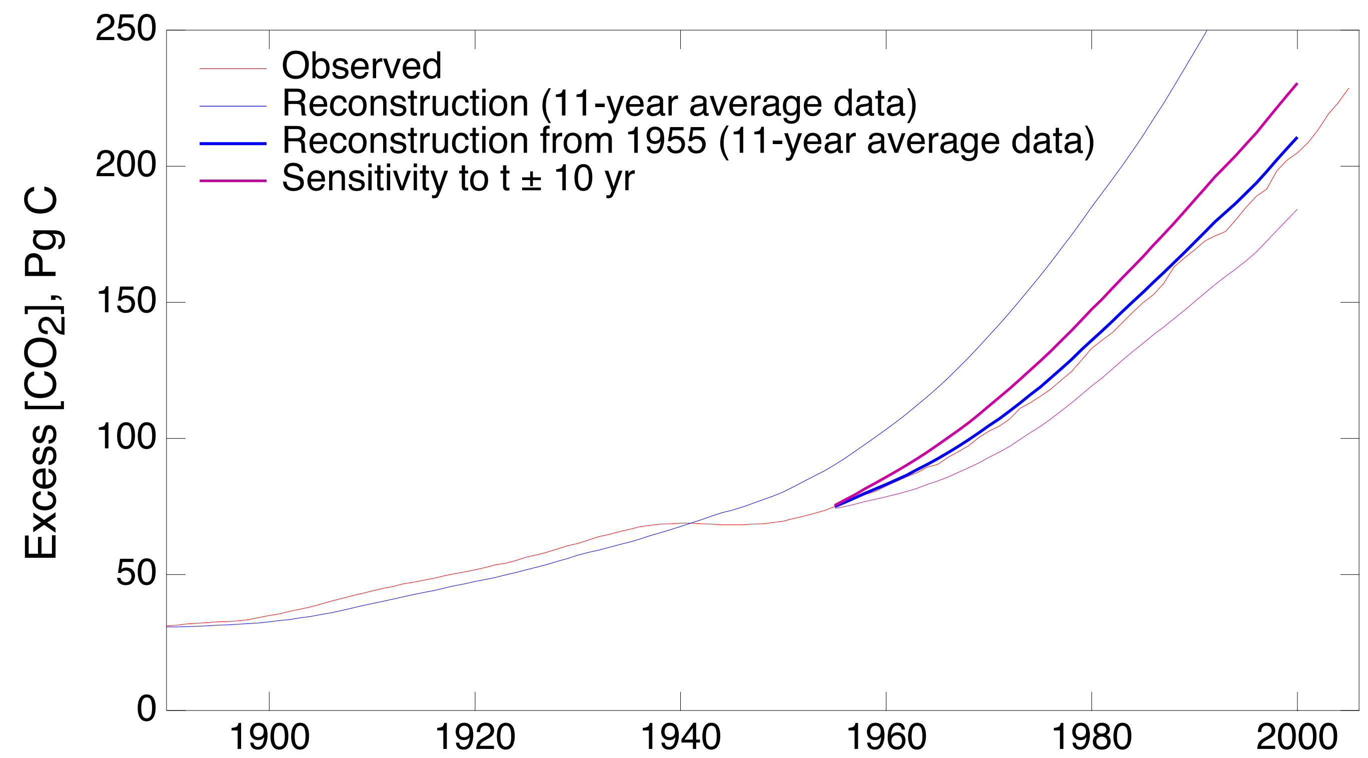
Green's function that can be convolved with emissions to calculate future atmospheric CO_2 mixing ratio for known or assumed emissions.

For most substances the annual decrease is proportional to the amount present; the decay rate constant is a constant; the impulse response function is exponential decay.

For CO_2 the decay rate constant is commonly stated (e.g., Bern Model) to decrease at longer times subsequent to emission as the oceans become saturated in excess CO_2. Constant excess CO_2 at long time is due to saturation of the ocean, with little net biological sink.



How well does the model reproduce the observations?



11-Year running average works well from 1955 but does not capture dip in excess CO_2 in 1940's.

Can we trust the data?

Questioning the data -- The last refuge of a modeler

- The Law Dome CO_2 data actually show a slight decrease in CO_2 in the early 1940's, despite emissions comparable to prior years.
- Can these data be trusted?
- This situation calls for re-examination of CO_2 in glacial ice cores.